

Charge Quantum Interference Device

S. E. de Graaf^{1,*}, S. T. Skacel², T. Hoenigl-Decrinis^{1,3}, R. Shaikhaidarov^{3,4}, H. Rotzinger², S. Linzen⁵, M. Ziegler⁵, U. Hübner⁵, H.-G. Meyer⁵, V. Antonov^{3,6}, E. Il'ichev^{5,7}, A. V. Ustinov^{2,7}, A. Ya. Tzalenchuk^{1,3}, O. V. Astafiev^{1,3,4,7}

¹*National Physical Laboratory, Hampton Road, Teddington, Middlesex TW11 0LW, UK*

²*Physikalisches Institut, Karlsruhe Institute of Technology, D-76128 Karlsruhe, Germany*

³*Department of Physics, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK*

⁴*Moscow Institute of Physics and Technology, 141700, Dolgoprudny, Moscow region, Russia*

⁵*Leibniz Institute of Photonic Technology, P.O. Box 100239, D-07702 Jena, Germany*

⁶*Skolkovo Institute of Science and Technology, Nobel str. 3, Moscow, 143026, Russia*

⁷*Russian Quantum Center, National University of Science and Technology MISIS, Moscow 119049, Russia*

The demonstration of coherent quantum phase slips (CQPS) in disordered superconductors has opened up a new route towards exploring the fundamental charge-phase duality in superconductors with the promise of devices with new functionalities and a robust quantum current standard based on CQPS. Here we show a device that integrates several CQPS junctions: the Charge Quantum Interference Device (CQUID). The CQUID becomes the dual to the well known superconducting quantum interference device (SQUID), and is a manifestation of the Aharonov-Casher effect in a continuous superconducting system void of dielectric barriers.

Superconductivity in metallic nanowires is strongly influenced by fluctuations of the superconducting order parameter [1]. Thermally Activated Phase Slips (TAPS) are dominant near the superconducting transition temperature, T_c [2]. Well below T_c the phase of a homogeneous superconducting wire can slip by 2π due to quantum tunnelling, a process dual to Cooper-pair tunnelling in Josephson junctions [3]. The notion of coherent phase slips in nanowires proposed by Mooij and Nazarov [4] was supported by experiments by Astafiev et al. [5] with wires made of nominally homogeneous superconducting material. Such coherent quantum phase slips (CQPS), carried by tunneling of magnetic fluxons across a superconducting wire, enable devices based on quantum interference effects, opening a route towards a wide range of quantum devices dual to those that can be implemented with Josephson junctions [4, 6, 7].

Quantum interference of Cooper-pairs in flux-based superconducting quantum interference devices (SQUIDs) was demonstrated soon after the discovery of the Josephson effect [8] and has since become a cornerstone of superconducting electronics. Another cornerstone is the locking of the phase across the Josephson junction to an external microwave field, resulting in Shapiro steps at quantised voltages [9]. This effect is used in high-frequency amplifiers, detectors and as the basis for the quantum voltage standard, which today underpins the electronics industry [10]. The main motivation for studying CQPS and dual superconducting devices has so far been the promise of a robust quantum *current* standard based on so-called 'dual Shapiro steps' [4, 11–13], complementary to the Josephson voltage standard. Although this particular goal has not yet been achieved, the experimental observation of CQPS in superconducting nanowires [5] has advanced the understanding of one-dimensional

superconductivity and coherence in disordered superconductors [14, 15] to the level when dual superconducting electronics has now become a possibility.

Conventional *dc* SQUIDs can be viewed as a specific implementation of the Aharonov-Bohm (AB) effect [16], where interference of the wave-function of a moving charged particle occurs when it encircles a flux (Fig. 1a). In contrast, the Aharonov-Casher (AC) effect, where the interference of fluxon trajectories, occurs around a static charge [17], is the dual to the AB effect. The AC effect has previously been observed in a variety of particle and solid-state systems [18–21] and in Josephson junction arrays [22–26]. Here we demonstrate the AC effect in a nominally continuous superconductor for the first time. Our device comprises two series CQPS junctions in which we achieve charge-controlled interference of fluxon tunneling in a device exactly dual to the SQUID. We call this device the Charge QUantum Interference Device (CQUID). This coherent charge-sensitive interferometer demonstrates the potential of CQPS devices previously only explored through the approximate [4] self-duality of Josephson junction circuits [12, 22, 27–31]. Such arrays of Josephson junctions has shown to be challenging complementary route towards a quantum current standard based on quantum phase slips [32].

In the CQUID, schematically shown in Fig. 1b, flux coherently tunnels across two narrow constrictions in a superconducting wire that we conclude is continuous in the superconducting order parameter (see evidence in Supplemental material). The two constrictions, of size $\sim 30 \times 50$ nm, are connected in series and made out of a continuous ~ 3.3 nm NbN film. These constrictions provide well-defined points with an increased phase slip amplitude [15]. The wider, ~ 100 nm, region ('island') between the constrictions is coupled through the capacitance C_g to a gate electrode. The island is made large enough to prohibit phase slips, but small enough to minimise its self-capacitance shunting the CQUID. Such a shunt capacitance would reduce the impedance

* sdg@npl.co.uk

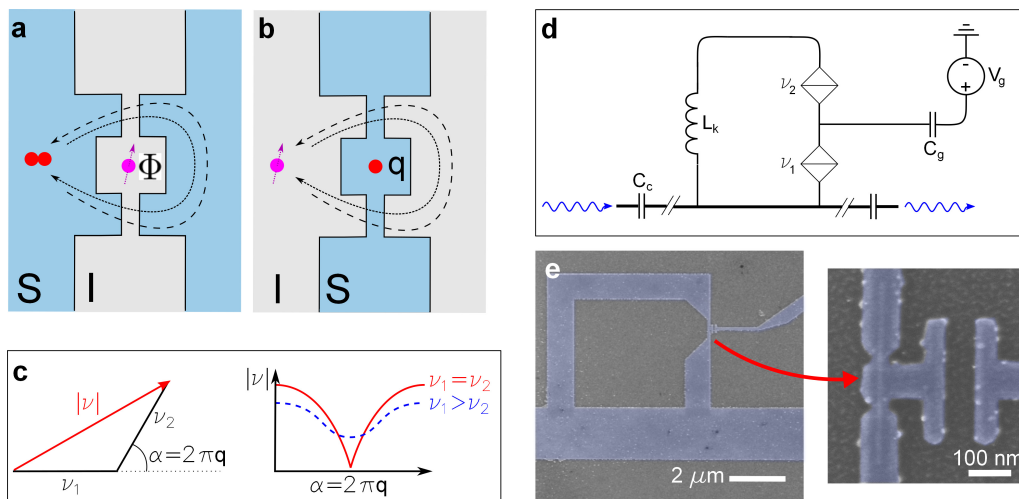


FIG. 1. Duality & sample design. **a** The interference effect in a SQUID. The flow of Cooper-pairs around a flux results in critical current fluctuations. I and S denotes insulator and superconductor respectively. **b** A schematic representation of the dual CQUID. The phase interference result from flow of flux around a charge. **c** Phase-slip amplitude interference represented as two complex phasors. Equal phase-slip amplitudes of the two junctions result in a $|\cos 2\pi q|$ dependence of the total measured phase-slip rate (solid line) while dissimilar amplitudes will yield a weaker dependence (dashed line) tending towards a sinusoidal dependence. **d** Circuit representation of our device. **e** False color electron micrograph of the device and a close-up on the CQPS junctions and the gated island. Blue indicates the NbN film.

and renormalise the phase slip amplitude of the device.

The charge induced by the gate potential V_g controls the interference of the phase slip amplitudes, with a period of $2e$, in much the same way as the effective Josephson energy in the SQUID is tuned by an external magnetic flux, with the period of Φ_0 , the flux quantum. Each interferometer becomes indistinguishable to its dual counterpart by the dual single particle exchange (Cooper pair or fluxon) with the following additional substitutions: current (Cooper-pair flow) \leftrightarrow voltage (flux flow), charge \leftrightarrow magnetic flux, Josephson energy \leftrightarrow phase-slip energy and insulator \leftrightarrow superconductor [4]. This also implies that the lack of flux quantization in the SQUID translates to the absence of charge quantization in the dual device, and the induced charge on the island (normalised to $2e$) precisely follows $q = C_g V_g / 2e$, where V_g is the applied gate voltage.

In much the same way as the insulator in a superconductor-insulator-superconductor (SIS) junction provide a tunnel barrier for Cooper pairs (but not for fluxons), a continuous superconductor provides a tunnel barrier for fluxons (but not for Cooper pairs). Observation of CQPS requires a low barrier for flux tunnelling across the superconductor, realised by a high kinetic inductance. This is achieved in highly disordered superconducting films close to the superconductor-insulator transition (SIT) [14, 15]. The same magnitude of the phase slip amplitude can be realised in a wider constriction for superconductors close to the SIT, easing fabrication requirements and increasing reproducibility due to the exponential dependence of phase slip amplitude on constriction width [14]. By using Atomic Layer Deposi-

tion (ALD) grown NbN films [33–35], we can now controllably make high quality films that are very close to the SIT, enabling fabrication of multiple very similar CQPS constrictions in the same device using conventional nanofabrication techniques. We have verified the continuity of the superconducting order parameter in our films in independent measurements on microbridges. Specifically for the CQUID devices presented here we also confirmed that the phase slip energy in the CQUID persists up to magnetic fields much larger than would be possible for a small-area Josephson junction, confirming that our CQPS junctions are indeed constrictions in a continuous film. We refer the reader to the Supplemental material for further details.

Essential for the realisation of a current standard based on CQPS are DC transport measurements [4, 13, 31, 36–38], however, these are often complicated by incoherent effects such as Coulomb blockade and dissipation. To demonstrate CQPS interference in the CQUID we instead follow the methodology of Refs. [5, 14, 15] and use microwave spectroscopy which provides a tool for measuring the tunnelling energy in quantum systems. In particular, the Cooper pair box connected to a reservoir via a SQUID allows to control and measure the Cooper pair tunnelling energy (Josephson energy) of the SQUID [39]. We develop an exact dual measurement circuit: the CQUID is implemented in a loop with a high but finite inductance. The resulting flux states provides an orthogonal degree of freedom to the energy spectrum of the CQUID and the fluxon flow due to CQPS. The circuit allows us to directly measure the tunnelling energy of the CQUID (tunnelling energy of fluxons), see Supplemen-

tary material for details. In addition, a high-impedance environment for flux tunnelling is achieved by embedding the loop in a $\lambda/2$ superconducting resonator, made from the same NbN film. The resonator allows for direct read-out of the energy spectrum of the device by dispersive microwave spectroscopy [5, 14, 15].

The reduced Hamiltonian describing our device in the flux basis is $H = -E_L\sigma_z/2 - E_s\sigma_x/2$ [6, 40], where σ_i are the Pauli matrices, $E_s = h|\nu_{\text{tot}}|$ is the coupling energy due to the phase-slip amplitude ν_{tot} and $E_L = 2I_p\delta\Phi$ is the inductive energy due to the persistent current $I_p = \Phi_0/2L_k$ in the loop with inductance L_k and $\delta\Phi = \Phi_{\text{ext}} - (N + 1/2)\Phi_0$. N is the number of magnetic flux quanta Φ_0 in the loop subjected to a magnetic flux Φ_{ext} tuned by an external solenoid. The energy difference between the ground and the first excited state of the diagonalised Hamiltonian is $\Delta E = ((2I_p\delta\Phi)^2 + E_s^2)^{1/2}$. When introducing two discrete arbitrary phase-slip junctions in series separated by an island the lowest energy level transition in the ring becomes

$$\Delta E = \sqrt{(2I_p\delta\Phi)^2 + h^2|\nu_1 + \nu_2 e^{i2\pi q}|^2}, \quad (1)$$

where we use $\nu_{\text{tot}} = \nu_1 + \nu_2 e^{i2\pi q}$ [22, 30, 41]. ν_1 and ν_2 are the bare phase-slip amplitudes for the two junctions respectively and q is the charge (normalised to $2e$) induced on the island. Importantly, the phase-slip rate depends on the gate induced charge only. This is a direct result of the the non-quantised charge and Cooper pairs are not localised on the island. The expected $2e$ -periodic oscillations due to the induced charge on the island is a result of the phase-slip amplitude interference across the two junctions. We note that eq. (1) applies to both CQPS and Josephson junction chains, and a distinction of the underlying physics could not solely be based on eq. (1). We refer the reader to our Supplemental material for a thorough discussion on the nature and homogeneity of our CQPS junctions.

The case of symmetric phase slip amplitudes ($\nu_1 = \nu_2$) reduces for $\delta\Phi = 0$ to $\Delta E \propto |\cos \pi q|$, in exact duality to the flux-modulated critical current of a magnetic SQUID with two identical Josephson junctions. For certain values of q we would thus expect the transition energy to be suppressed to zero. For largely dissimilar phase-slip amplitudes ($\nu_1 \gg \nu_2$), or in the presence of non-trivial flux bias $\delta\Phi \neq n\Phi_0$ (where n is an integer number), the variation in ΔE due to the induced charge instead resembles a sinusoidal dependence, as sketched in Fig. 1c. We now proceed to the measurements of our device which are in very good agreement with these expectations.

Figures 2a and 2b show the measured energy level spectroscopy data as a function of magnetic flux for two different applied gate voltages. From the asymptotically linear dependence of the energy level transitions on magnetic flux, we extract $I_p = 30$ nA and $L_k = 33$ nH corresponding to the inductance per square of the NbN film $L_\square = 1.35$ nH. BCS theory underestimates L_k near the SIT [42]. From the normal state per square resistance

$R_\square = 2.3$ k Ω measured above the critical temperature T_c , we get $L_\square = \hbar R_\square / (\pi \Delta_{\text{BCS}}) = 0.67$ nH for $T_c = 4.7$ K, different by a factor 2. Figure 2c shows the full response of the energy levels due to the induced charge on the island at $\delta\Phi = 0$. Notably, for each gate voltage we find two spectroscopy lines that deviate out of phase with each other in gate voltage. These lines are shifted in charge by exactly half-a-period, which is explained by charge interference (AC effect) and the presence of non-equilibrium quasiparticles. A change in the number of non-equilibrium quasiparticles N_{qp} present on the island will change the overall island charge by $1e$ and the AC phase by π . Depending on the charge number parity of the island [43, 44], we observe two different parity bands according to $\nu_{\text{tot}} = \nu_1 + (-1)^{N_{\text{qp}}}\nu_2 e^{i2\pi q}$. This is similar to what has been observed in charge qubits [45]. In the complex amplitude representation of the phase-slip amplitude of equation (1) shown in Fig. 2e, such parity shifts result in two phase-slip amplitudes rotated by exactly π . The two bands are maximally separated at an induced island charge of precisely $q = ne$, where n is an integer.

The oscillations provide compelling evidence for flux interference, the fundamental mechanism on which the CQUID is based, and is a demonstration of the AC-effect in a solid state system without insulating tunneling barriers [18, 22]. This is further evidenced by Fig. 2d showing the fit of the data in Fig. 2c to equation (1). We extract the two phase-slip amplitudes $\nu_1 = 9.2$ and $\nu_2 = 3.3$ GHz. This strong similarity in phase-slip amplitudes allows us to accurately compare the CQUID operation with theoretical predictions.

We may express the phase slip energy of a single constriction in terms of the dimensionless conductance $g_\xi = R_q/R_\xi$ of a wire segment of length ξ , where $R_q = h/4e^2$ is the superconducting resistance quantum [1]: $E_s = (\Delta g_\xi) \exp(-ag_\xi)$. Here the dimensionless parameter $a \approx 0.3$ [6, 46] is only weakly dependent on the environment of the phase slip junction. For the measured phase slip amplitudes of 3.3 and 9.2 GHz and for junction dimensions of 46×30 and 39×30 nm respectively we obtain $a \approx 0.29$, in excellent agreement with the observed dimensions and the expected value for a .

As we move the flux bias away from the degeneracy point we expect that the variation in transition energy with induced charge on the island is suppressed. In Fig. 3a we show the difference in transition energy at the maximum and minimum of eq. (1) with respect to the gate-induced charge q as a function of flux detuning $\delta\Phi_0$ and in Fig. 3b the measured and expected deviation of equation (1) from a pure sinusoidal dependence of ΔE on q . Both datasets are in exceptionally good agreement with equation (1). The transition line-width is $\delta E/h = 200$ MHz in the weak drive limit for both the even and odd parity modes and their occupation probabilities are the same (Fig. 3c). This linewidth is similar to that obtained in previous experiments, where CQPS has been studied [5, 14, 15].

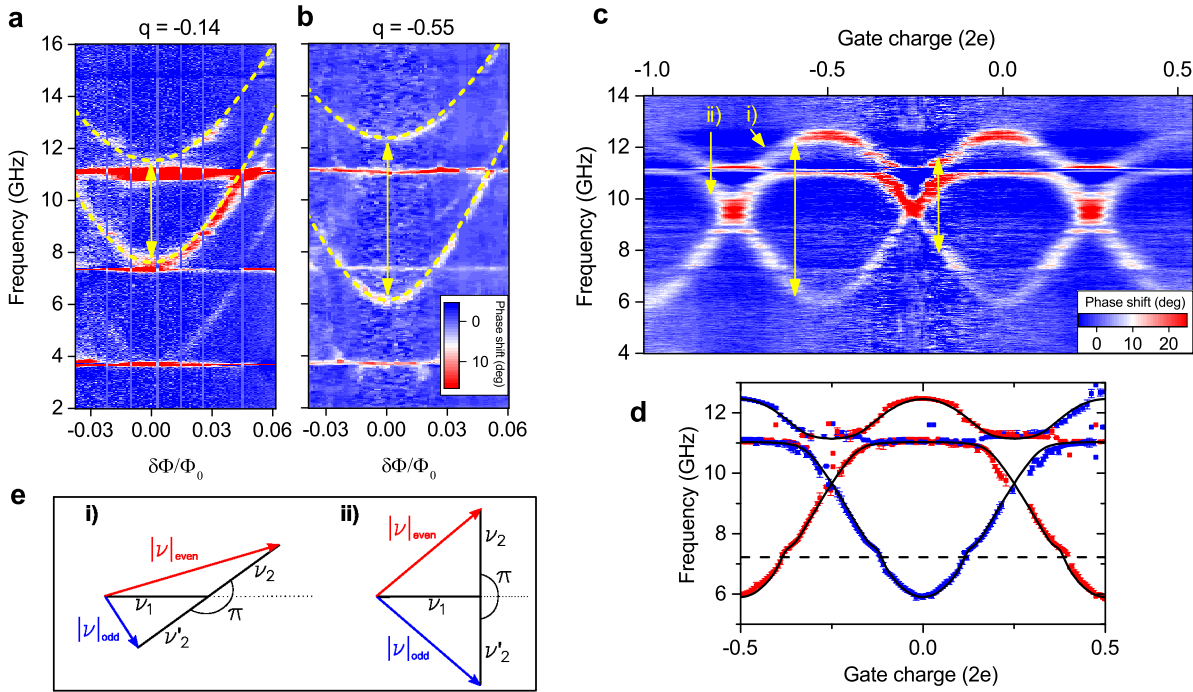


FIG. 2. Energy level spectroscopy of the CQUID. **a** and **b** Spectroscopy data of the same device for two different applied gate voltages (different island charge q). Readout is performed by two-tone microwave spectroscopy with a weak probe tone at the fundamental resonance frequency of 3.7 GHz. The resonator had a quality factor of 600. Dashed lines are fits to equation (1), the only difference between the four dashed lines is the charge q , all other fitting parameters are the same. Other parabolic spectroscopy lines visible are due to higher order energy level transitions and horizontal lines are resonator modes. **c** Two-tone microwave spectroscopy phase variation data taken at $\delta\Phi = 0$ as a function of induced charge on the island. Double-sided arrows indicate the identical working points in **a** and **b**. **d** Extracted transition frequencies for the even (red) and odd (blue) parity states. Solid lines are fits to equation (1) where we have also included hybridisation with the third resonance mode at 11 GHz (coupling strength $g = 225$ MHz) and weak coupling to the second resonance mode (dashed line at 7.3 GHz, $g \approx 70$ MHz). Error bars indicate 95% confidence bounds to the fits of peak positions in **c**. **e** Geometric construction of the two parity states even (red) and odd (blue) in the CQUID shifted by a phase π in the complex plane. i) and ii) are for two different gate charges indicated in **c**.

The origin of the parity fluctuations can be understood by considering the nature of the junctions in the device. We may introduce an arbitrary number of quasiparticles on the CQUID island without paying any additional electrostatic energy. Instead, the normal state resistance determines the time which a non-equilibrium quasiparticle spends on the island (in the absence of recombination, which is parity-conserving). We may estimate the shortest quasiparticle dwell time on the island as $\tau_{qp} \approx e^2 R_{\square} V \rho \approx 2$ ns, where $\rho = 3.8 \cdot 10^{47} \text{ J}^{-1} \text{ m}^{-3}$ [47] is the density of states in NbN at the Fermi energy, $V \approx 10^{-22} \text{ m}^3$ is the volume of the island. Thus, in the presence of non-equilibrium quasiparticles in the leads, we expect to have a rapidly fluctuating number of quasiparticles N_{qp} on the CQUID island, leading to the observed behaviour of equal probabilities for the two parities over the much longer measurement timescale.

The quasiparticle dwell time is comparable to the co-

herence time $\tau \simeq 5$ ns we observe in our time-averaged measurements, extracted from the transition line-width.

In addition to parity fluctuations, we observe large fractional charge jumps on a time-scale of ~ 1 hour due to charge fluctuators in the surrounding dielectrics, a clear indication that offset charge fluctuations in long wires will affect the coherences and phase slip amplitudes analogous to what has been found for Josephson junction chains [32, 48].

We have demonstrated control of the interference of coherent quantum phase slip amplitudes in a charge quantum interference device comprised of two CQPS junctions. The excellent agreement with theory and large response due to the induced island charge is compelling evidence for the AC-effect in a continuous highly disordered superconducting system. This demonstration of duality and the CQUID is an important step towards a future quantum current standard based on CQPS, however, the

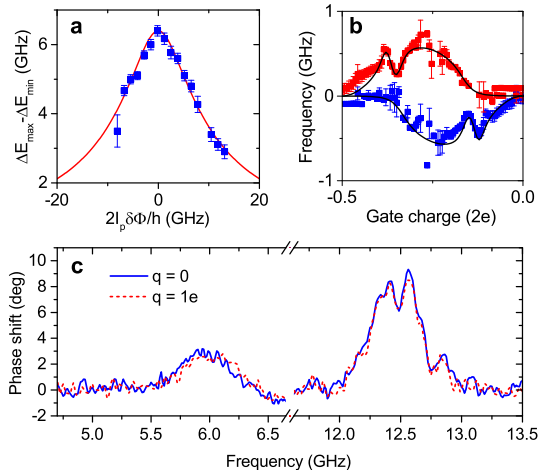


FIG. 3. Fit to theory and parity state population. **a** The measured maximum difference in transition frequency, obtained at induced gate charges of 0 and 1e respectively, as a function of flux detuning from the degeneracy point $\delta\Phi = 0$. Error bars are observed transition line-widths. Red solid line is fit to equation (1). **b** The deviation of the two lower modes from a pure sinusoidal gate dependence of $E_s(q)$. The sharp kink is due to the coupling to the second resonance mode. Error bars indicate 95% confidence bounds to the fits of peak positions in Fig. 2c. **c** Two-tone phase response for two induced gate charges showing equal populations of the two parity states. Difference in high and low frequency peak amplitudes are due to different coupling strengths to the resonator mode.

observed strong quasiparticle poisoning may provide an additional obstacle towards its realisation. Quasiparticle poisoning may lead to a spurious quasiparticle current and perturbations to the phase locking of Bloch oscillations [48]. Quasiparticle poisoning is thus an engineering challenge that needs to be addressed using quasiparticle trapping and elimination techniques. By placing the coherent CQUID in a high-impedance environment for DC measurements it can be used as a route towards a CQPS-based current standard.

ACKNOWLEDGEMENTS

This work was supported by the UK government’s Department for Business, Energy and Industrial Strategy. We thank Y. Nazarov and A. Semenov for fruitful discussions. STS thanks S. Diewald and L. Radtke for their technical support during fabrication and acknowledges support from the Heinrich Böll Foundation and the Karlsruhe House of Young Scientists (KHYS). This work was partially supported by the Increase Competitiveness Program of NUST MISiS (grants no. K2-2015-002 and 2-2016-051).

AUTHOR CONTRIBUTIONS

OVA, SedG and AT conceived the experiment, SedG designed the samples performed the measurements with assistance from STS, TH-D, RS, VA and OVA, and analysed the data. SL, MZ, UH, HGM and EI developed the thin film technology. STS fabricated the samples with assistance from HR and RS. SedG wrote the manuscript with input from OVA, STS, and all other authors. All authors discussed the results.

COMPETING FINANCIAL INTERESTS

The authors declare that they have no competing financial interests.

METHODS

Thin film technology. The NbN thin-films were deposited on undoped Si(100) by plasma enhanced atomic layer deposition (PEALD). An OpAL ALD system by Oxford Instruments Plasma Technology upgraded with a remote plasma source (ICP) and a nitrogen glove box were used. The metal-organic compound (tertbutylimido)-tris (diethylamino)-niobium (TBTDEN) and an hydrogen plasma were applied as precursors. The NbN ALD process is based on a self-limiting surface reaction principle with a well-controlled layer growth of 0.46 Å per cycle. Thus, for the CQUID experiments superconducting NbN layers of only 3.3 nm film thickness were prepared within an ALD process of 72 cycles. The prepared layers have a granular film structure. More details are described in Refs. [33] and [35] and the Supplemental material. The precise adjustment of chemical composition, crystal structure and film thickness allows to produce NbN layers with the above reported high values of critical temperature T_c , normal state resistance R_{\square} and inductance L_{\square} , essential for realising the CQUID.

Device fabrication. To pattern the CQUID device we used electron beam (e-beam) lithography. A 50 nm layer of the negative e-beam resist hydrogen silsesquioxane (HSQ) was exposed by a 50 keV beam in a JEOL JBX-5500ZD e-beam lithography system. The resonator, the loops and the islands as well as the gate electrodes are exposed with a dose of 900 $\mu\text{C}/\text{cm}^2$ while the constrictions are defined by doses between 8.6 – 31.5 mC/cm^2 . This gives constriction widths in the range of 50 – 70 nm. After the HSQ development (MicroChemicals AZ 726 MIF), the coplanar ground-planes and the microwave and bias gate pads are defined by optical lithography utilizing a standard lift-off technique. The ground planes and contact pads are made by thermal evaporation of a 5 nm titanium (Ti) adhesion layer and an 80 nm gold (Au) layer in a Plassys MEB 550 S evaporator. During this step, the resonator and the loops with constrictions are protected

by the optical resist. After lift-off, the resonator and the loops with constrictions, islands and gates are defined in the NbN film by reactive ion etching (RIE) using an Oxford Instruments Plasmalab 80 Plus. The HSQ acts as a hardmask against the reactant fluorine ($\text{CF}_4:\text{Ar}$, 10:1) in the RIE process which etches the NbN much faster than the HSQ. All Au covered areas are protected since Au is inert against fluorine RIE. Test structures for DC measurements were co-fabricated on the same films, from which we extract the critical temperature T_c and normal state resistance R_\square measured just above T_c .

Measurements. Samples were mounted in a dilution refrigerator with a base temperature of 20 mK, essential for maximising the coherence of the device, and minimising the effect of thermally activated phase slips. Samples were shielded by both superconducting and cryo-erm shields to minimise noise in the flux threading the loops. Heavily attenuated coaxial lines were used for microwave excitation and the transmitted signal was passed through two cryogenic isolators before being amplified by

a cryogenic HEMT amplifier at 4 K. The gate voltages were applied through low-pass filtering Thermocoax lines with additional low pass filtering at the mixing chamber stage. The measured gate period ($2e$) at the sample was 60.1 mV giving an effective gate capacitance of 5 aF, in good agreement with finite element electrostatic calculations of the total capacitance as seen by the island of 20 aF, that also includes the contributions from the gate capacitance. The dispersive readout of the resonator is performed by applying a weak probe tone at the fundamental resonance frequency of 3.74 GHz that monitors the phase shift of the resonator (using a vector network analyser) in response to a strong tone that induce transitions in the loop's energy spectrum. The particular loop presented in this manuscript was identified by its flux periodicity, matched to the designed loop area. This particular sample had 6 loops with working constrictions, allowing for easy identification.

Data availability. Experimental data is available from the corresponding author upon reasonable request.

-
- [1] Arutyunov, K. Yu., Golubev, D. S. and Zaikin, A. D. Superconductivity in one dimension. *Phys. Rep.* **464**, 1-70 (2008).
- [2] McCumber, D. E. and Halperin, B. I. Time Scale of Intrinsic Resistive Fluctuations in Thin Superconducting Wires. *Phys. Rev. B* **1**, 1054-1070 (1970).
- [3] Martinis, J. M., Devoret, M. H. and Clarke, J. Experimental tests for the quantum behavior of a macroscopic degree of freedom: the phase difference across a Josephson junction. *Phys. Rev. B* **35**, 4682-4698 (1987).
- [4] Mooij, J. E. and Nazarov, Yu. V. Superconducting nanowires as quantum phase-slip junctions, *Nature Physics* **2**, 169-172 (2006).
- [5] Astafiev, O. V., et al. Coherent quantum phase slip, *Nature (London)* **484**, 355-358 (2012).
- [6] Mooij, J. E., and Harmans, C. J. P. M. Phase-slip flux qubits, *New J. Phys.* **7**, 219 (2005).
- [7] Hriscu, A. M., and Nazarov, Yu. V. Coulomb blockade due to quantum phase slips illustrated with devices, *Phys. Rev. B* **83**, 174511 (2011).
- [8] Jaklevic, R. C., Lambe, J., Silver, A. H., and Mercereau J. E. Quantum interference effects in Josephson tunneling. *Phys. Rev. Lett.* **12**, 159-160 (1964).
- [9] Shapiro, S. Josephson currents in superconducting tunneling: The effect of microwaves and other observations, *Phys. Rev. Lett.* **11**, 80-82 (1963).
- [10] Kohlmann, J., Behr, R., and Funck, T. Josephson voltage standards, *Meas. Sci. Tech.* **14**, 1216 (2003).
- [11] Gallop, J. C., SQUIDS, the Josephson effects and superconducting electronics (IOP publishing Ltd., Bristol, 1990).
- [12] Ergül, A., et al. Localising quantum phase slips in one-dimensional Josephson junction chains, *New J. Phys.* **15**, 095014 (2013).
- [13] Webster, C. H., et al. NbSi nanowire quantum phase slip circuits: dc supercurrent blockade, microwave measurements, and thermal analysis, *Phys. Rev. B* **87**, 144510 (2013).
- [14] Peltonen, J. T., et al. Coherent flux tunneling through NbN nanowires, *Phys. Rev. B* **88**, 220506 (2013).
- [15] Peltonen, J. T., et al. Coherent dynamics and decoherence in a superconducting weak link, *Phys. Rev. B* **94**, 180508 (2016).
- [16] Aharonov, Y., and Bohm, D. Significance of electromagnetic potentials in the quantum theory, *Phys. Rev.* **115**, 485-491 (1959).
- [17] Aharonov, Y., and Casher, A. Topological quantum effects for neutral particles, *Phys. Rev. Lett.* **53**, 319-321 (1984).
- [18] Elion, W. J., Wachtters, J. J., Sohn, L. L., and Mooij, J. E. Observation of the Aharonov-Casher effect in vortices in Josephson-junction arrays, *Phys. Rev. Lett.* **71**, 2311-2314 (1993).
- [19] Cimmino, A., et al. Observation of the topological Aharonov-Casher phase shift by neutron interferometry, *Phys. Rev. Lett.* **63**, 380-383 (1989).
- [20] Sangster, K., Hinds, E. A., Barnett, S. M., and Riis, E. Measurement of the Aharonov-Casher phase in an atomic system, *Phys. Rev. Lett.* **71**, 3641-3644 (1993).
- [21] König, M., et al. Direct observation of the Aharonov-Casher phase, *Phys. Rev. Lett.* **96**, 076804 (2006).
- [22] Pop, I. M., et al. Experimental demonstration of Aharonov-Casher interference in a Josephson junction circuit, *Phys. Rev. B*, **85**, 094503 (2012).
- [23] Bell, M. T., Zhang, W., Ioffe, L. B., and Gershenson, M. E. Spectroscopic evidence of the Aharonov-Casher effect in a Cooper pair box, *Phys. Rev. Lett.* **116**, 107002 (2016).
- [24] Born, D. et al. Reading out the state inductively and microwave spectroscopy of an interferometer-type charge qubit. *Phys. Rev. B* **70**, 180501 (2004).
- [25] Manucharyan, V. E., Koch, J., Glazman, L. I. and Devoret, M. H. Fluxonium: Single Cooper-Pair circuit free of charge offsets. *Science* **326**, 113-116 (2009).
- [26] Manucharyan, V. E., Nicholas A. Masluk, N. A., Kamal, A., Koch, J., Glazman, L. I. and Devoret, M. H. Evi-

- dence for coherent quantum phase slips across a Josephson junction array. *Phys Rev. B* **85**, 024521 (2012).
- [27] Masluk, N. A., Pop, I. M., Kamal, A., Mineev, Z. K., and Devoret, M. H. Microwave characterisation of Josephson junction arrays: Implementing a low loss superinductance, *Phys. Rev. Lett.* **109**, 137002 (2012).
- [28] Kerman, A. J. Fluxcharge duality and topological quantum phase fluctuations in quasi-one-dimensional superconductors. *New J. Phys.* **15** 105017 (2013).
- [29] Guichard, W. and Hekking, F. W. J. Phase-charge duality in Josephson junction circuits: Role of inertia and effect of microwave irradiation. *Phys. Rev. B* **81**, 064508 (2010).
- [30] Friedman, J. R. and Averin, D. V. Aharonov-Casher-Effect Suppression of Macroscopic Tunneling of Magnetic Flux. *Phys. Rev. Lett.* **88**, 050403 (2002).
- [31] Weißl, T., Rastelli, G., Matei, I., Pop, I. M., Buisson, O., Hekking, F. W. J. and Guichard, W. Bloch band dynamics of a Josephson junction in an inductive environment. *Phys. Rev. B* **91**, 014507 (2015).
- [32] Cedergren, K., Ackroyd, R., Kafanov, S., Vogt, N., Shnirman, A. and Duty, T. Insulating Josephson junction chains as pinned Luttinger liquids. *Phys. Rev. Lett.* **119**, 167701 (2017).
- [33] Linzen, S. et al. Structural and electrical properties of ultrathin niobium nitride films grown by atomic layer deposition, *Supercond. Sci. Technol.* **30**, 035010 (2017).
- [34] Ziegler, M., et al. Superconducting niobium nitride thin films deposited by metal organic plasma-enhanced atomic layer deposition, *Supercond. Sci. Technol.* **26**, 025008 (2013).
- [35] Ziegler, M. et al. Effects of plasma parameter on morphological and electrical properties of superconducting NbN fabricated by MO-PEALD. *IEEE Trans. Appl. Supercond.* **27**, 7501307 (2017).
- [36] Hongisto, T. T. and Zorin, A. B. Single-Charge transistor based on the charge-phase duality of a superconducting nanowire. *Phys. Rev. Lett.* **108**, 097001 (2012).
- [37] Lehtinen, J. S., Zakharov, K. and Arutyunov, K. Yu. Coulomb Blockade and Bloch Oscillations in Superconducting Ti Nanowires. *Phys. Rev. Lett.* **109**, 187001 (2012).
- [38] Kafanov, S. and Chtchelkatchev, N. M. Single flux transistor: The controllable interplay of coherent quantum phase slip and flux quantization. *J. Appl. Phys.* **114**, 073907 (2013).
- [39] Nakamura, Y., Pashkin, Yu. A. and Tsai, J. S. Coherent control of macroscopic quantum states in a single-Cooper-pair box. *Nature* **398**, 786-788 (1999).
- [40] Hu, Z., Tie-Fu, L., Jian-She, L., and Wai, C., Charge-related SQUID and tunable phase-slip flux qubit, *Chinese Phys. Lett.* **31**, 030303 (2014).
- [41] Matveev, K. A., Larkin, A. I., and Glazman, L. I. Persistent current in superconducting nanorings, *Phys. Rev. Lett.* **89**, 096802 (2002).
- [42] Sacépé, B., et al. Localization of preformed Cooper pairs in disordered superconductors, *Nature Physics* **7**, 239-244 (2011).
- [43] Eiles, T. M., Martinis, J. M. and Devoret, M. H. Even-odd asymmetry of a superconductor revealed by the Coulomb blockade of Andreev reflection. *Phys. Rev. Lett.* **70**, 1862-1865 (1993).
- [44] Hekking, F. W. J., Glazman, L. I., Matveev, K. A. and Shekhter, R. I. Coulomb blockade of two-electron tunneling. *Phys. Rev. Lett.* **70**, 4138-4141 (1993)
- [45] Sun, L. et al, Measurements of quasiparticle tunneling dynamics in a band-gap-engineered transmon qubit. *Phys. Rev. Lett.* **108**, 230509 (2012).
- [46] Vanjevic, M., and Nazarov, Y. V., Quantum phase slips in superconducting wires with weak homogeneities, *Phys. Rev. Lett.*, **108**, 187002 (2012).
- [47] Semenov, A. D., Goltsman, G. N. and Korneev, A. A. Quantum detection by current carrying superconducting film. *Physica C: Superconductivity*, **351**, 349-356 (2001).
- [48] Vora, H., Kautz, R.L., Nam, S.W. and Aumentado, J. Modeling Bloch Oscillations in Nanoscale Josephson Junctions. *Phys. Rev. B* **96**, 054505 (2017).

